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Table 1. Best-fit Parameters the Model Fits

Model	Parameter	Best fit (model 1)	Best fit (model 2)
Abs. Col.	$N_H[10^{22} \text{ cm}^{-2}]$	5.57 (-0.21, +0.19)	6.8 (-0.2, +0.3)
Thermal1.	kT(1)[keV]	10.5 (-1, +1)	0.97 (-0.03, +0.04)
	normalization	$8.9 \times 10^{-3}$	$1.8 \times 10^{-2}$
Thermal2	kT(2)[keV]	0.90 (-0.06, +0.05)	—
	normalization	$1.6 \times 10^{-2}$	—
Power law	—	—	$\alpha=1.38$ (-0.08, +0.07)
	amplitude	—	$1.7 \times 10^{-3}$
	Si/Si $\odot$	1.10 (-0.17, +0.25)	2.47 (-0.75, +1.2)
	S/S $\odot$	2.49 (-0.38, +0.58 )	2.76 (-0.78, +1.0 )
	Ar/Ar $\odot$	3.59 (-0.74, +1.0)	3.13 (-1.21, +1.28)
	Ca/Ca $\odot$	4.31 (-1.0, +1.26)	4.23 (-1.60, +1.87)
	Fe/Fe $\odot$	0.53 (-0.08, 0.08)	9.86 (-3.8, 7.3)
6.4 keV [Gaussian]	$\sigma$	0.13 (-0.02, +0.02)	0.15 (-0.04, +0.02)
	normalization	$1.1 \times 10^{-4}$	$1 \times 10^{-4}$
	chi-squared per degree of freedom	1.17	1.19

# The Origin of X-ray Emission from a Galactic Center Molecular Cloud: Low Energy Cosmic Ray Electrons

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## ABSTRACT

The Galactic center region near  $l \approx 0.2^\circ$  hosts a mixture of nonthermal linear filaments and thermal radio continuum features associated with the radio Arc. Chandra observations of this region reveal an X-ray filament and diffuse emission with an extent of roughly  $60'' \times 2''$  and  $5' \times 3'$ , respectively. The X-ray filament lies at the edge of the nonthermal radio filaments and a dense molecular shell G0.13-0.13 that has an unusually high kinetic temperature  $\geq 70\text{K}$ . These observations demonstrate that the G0.13–0.13 molecular cloud and the nonthermal radio filaments of the Arc are interacting. The diffuse X-ray emission is correlated with the molecular shell and is fitted either by two-temperature (1 and 10 keV) thermal emission or by power-law and 1 keV thermal gas. Fluorescent 6.4 keV line emission is also detected throughout the molecular shell. This cloud coincides within the error circle of a steady unidentified EGRET source 3EGJ1746–2851.

We argue that low-energy cosmic ray electrons (LECRE) produce the power-law continuum by bremsstrahlung and 6.4 keV line emission from the filament and the diffuse cloud with the implication on the origin of the Galactic ridge X-ray emission. The strong 6.4 keV Fe-line emission seen from other Galactic center clouds could be produced in a similar fashion rather than via fluorescent emission induced by a transient hard X-ray source in the Galactic center. In addition, heating by ionization induced by LECRe are also responsible for the high temperature of G0.13-0.13. The gamma-ray source is a result of bremsstrahlung by the high-energy tail of the electron energy distribution.

*Subject headings:* ISM: abundances—ISM: cosmic-rays—The Galaxy: center—Xrays: ISM



## 1. Introduction

The Galactic center radio continuum Arc is a complex system of thermal and nonthermal features distributed near  $l \approx 0.2^\circ$ . The nonthermal components of the Arc – the linear filaments – are long ( $> 15'$ ), narrow ( $\approx 5'' - 10''$ ) linearly polarized synchrotron emitting structures tracing organized magnetic fields which run perpendicular to the Galactic plane (Yusef-Zadeh, Morris and Chance 1984; Tsuboi *et al.* 1985; Sofue *et al.* 1986; Yusef-Zadeh and Morris 1987; Inoue *et al.* 1989; Reich *et al.* 2000). Recently, Tsuboi, Ukita and Handa (hereafter TUH; 1997) and Oka *et al.* (2001) have detected a CS and CO molecular cloud with a size of about  $3' \times 4'$  centered at G0.13-0.13 or G0.11-0.11, respectively. The G0.13-0.13 molecular cloud is about 7 pc in diameter (assuming a distance of 8 kpc) and is distinguished from other clouds within the inner  $30'$  of the Galactic center by exhibiting an enhanced kinetic temperature  $T_k \geq 70\text{K}$ , and relative isolation from the rest of clouds in the Galactic center (Oka *et al.* 2001). A morphological argument has been made for a site of interaction between a dense molecular shell G0.13-0.13 and the neighboring NTFs (TUH; Oka *et al.* 2001).

Here we present high resolution Chandra observations of the Galactic center radio Arc and report the detection of enhanced diffuse continuum and 6.4 keV line emission as well as filamentary X-ray emission from G0.13-0.13. Earlier ASCA X-ray observations suggested the presence of diffuse, hot (10 keV) X-ray gas throughout this region (Koyama *et al.* 1996). We present an alternative power-law and thermal fit to the diffuse X-ray gas in G0.13-0.13. In addition the power-law component and strong Fe 6.4 keV line are consistent with bremsstrahlung and collisional ionization by low-energy cosmic-ray electrons. The implication of such a mechanism to the origin of the hard X-ray emission from the Galactic ridge is also discussed. The associated heating explains the high kinetic temperature of the G0.13-0.13 molecular cloud. This is the strongest evidence yet of the interaction with

NTFs, leading us to identify the Galactic center EGRET source 3EGJ1746-2851 (Hartman *et al.* 1999) with the X-ray feature and G0.13-0.13 molecular cloud.

## 2. Observations and Results

An account of Chandra observations of the Galactic center Arc has been given earlier (Yusef-Zadeh *et al.* 2001). The X-ray spectrum was extracted from an almost-rectangular region, as shown in Figure 1. We used Sherpa to fit the extracted spectrum with either: (1) an absorbed power-law plus thermal model, using the MEKAL model for the thermal component (Mewe *et al.* 1985), or (2) using an absorbed, two temperature model. Each component of the two temperature fit was permitted to have different temperatures and volume emission measures, while the elemental abundances (Si, S, Ar, Ca, and Fe) were constrained to be identical for both components. For both both models (1) and (2), we added a Gaussian component fixed at 6.4 keV, to account for fluorescent Iron  $K\alpha$  line emission. Diffuse X-ray emission pervades the galactic center region making the extraction of a non-xray background nearly impossible. We accounted for the non-xray background by using the CXC’s “blank-sky” fields. The background spectrum was extracted from the same region as the source spectrum, in order to avoid any possible response-dependent affects.

An adaptively smoothed X-ray image of a region near G0.13-0.13 (right panel of Figure 1) shows diffuse X-ray emission distributed prominently in a rectangular area of  $\sim 5.3'^2$ . The full-resolution X-ray image of the same region (left panel) reveals a linear X-ray filament with a size of  $60'' \times 2''$ . A compact source is also detected toward the filament at (epoch 2000)  $\alpha = 17^h46^m21.56^s, \delta = -28^{\circ}52'56.8''$ . The enhanced diffuse and filamentary X-ray gas coincides with the CS and CO cloud G0.13–0.13 (TUH and Oka *et al.* 2001). The box drawn on Figure 1 shows the extent of G0.13-0.13 CS cloud. Figure 2 shows contours of CS (1–0) emission from the molecular cloud shell G0.13-0.13 with velocities in the range

$V_{LSR} = 15$  to  $45 \text{ km s}^{-1}$  (TUH). The contours are superimposed on a low-resolution X-ray distribution between 0.5 and 9 keV, which is displayed in greyscale. There is a strong spatial correlation between the diffuse X-ray gas and the CS line emission. The CS cloud is limb brightened and the X-ray images of Figure 1 show a strong X-ray filament to the north tracing the edge of the CS cloud. The estimated mass of the high density CS and the CO clouds are  $2\text{--}3.6 \times 10^5$  and  $10^6 M_{\odot}$ , respectively.

TUH argue that the northwestern limb of the CS molecular shell with a density of  $6 \times 10^4 \text{ cm}^{-3}$  is dynamically interacting with the Galactic center radio filaments because of the distorted structure as well as the large linewidth of the CS cloud, which exceeds  $40 \text{ km s}^{-1}$ . The enhanced kinetic temperature of the CO cloud G0.13-0.13 plus the abrupt velocity of the CS cloud at  $40 \text{ km s}^{-1}$  provide additional support to the idea that this is an unusual cloud and is possibly interacting with the NTFs (Oka *et al.* 2001). The X-ray and molecular gas distributions noted in Figure 2 also coincide with a steady source of strong  $\gamma$ -ray emission between 30 MeV and 10 GeV as detected by EGRET on board the *Compton Gamma Ray Observatory*. The cross in Figure 2 shows the position of 3EGJ1746-2851 (Hartman *et al.* 1999) with the error bar containing the 95% confidence contour. The photon index is  $\alpha = 1.7 \pm 0.7$ , and its flux is estimated to be  $1.2 \times 10^{-6} \text{ photons cm}^{-2} \text{ s}^{-1}$  with energies greater than 100 MeV, corresponding to  $10^{40} \text{ photons s}^{-1}$  at the distance of the Galactic center.

Figure 3 shows two different images of the fluorescent emission (Fe  $K\alpha$ ) at 6.4 keV. The left panel shows the fit value for the Gaussian normalization to each of these spectra and the right panel shows an adaptively smoothed 6.4 keV image. In general, the images correlate well, lending support to each method and in turn the correlation of 6.4 keV emission with the CS(1–0) contours. In particular, we note that each method shows three extended “blobs” in the SW edge of the CS cloud with strong 6.4 keV line emission. These blobs

with a size of  $\approx 1'$  do not show any obvious relation to point sources in the full-resolution data. The low-resolution 6.4 keV image produced from ASCA observations show 6.4 keV emission from this region (Koyama *et al.* 1996).

Figure 4 shows contours of the X-ray filament superimposed on the  $\lambda 20$ cm continuum image of the NTFs. The X-ray filament appears to be situated at the outer boundary but parallel to a number of small radio filaments having the same dimension as the X-ray filament. The nearest radio filament is displaced by  $\sim 15''$  from the X-ray filament but there is diffuse  $\lambda 90$ cm emission at a level of 200 to 245 mJy per  $41.7'' \times 22.7''$  beam area coincident with the X-ray filament (Anantharamaiah *et al.* 1991).

A spectrum shown in Figure 5 is extracted from the rectangular region of diffuse X-ray gas which is spread over four chips of the detector. This spectrum cover the densest region of the CS cloud G0.13-0.13. The point sources have been removed before the spectrum is fitted. The spectrum of the diffuse X-ray gas is equally-well fitted by two different models. One is thermal bremsstrahlung with two temperatures at 0.97 and 10.5 keV and a 6.4 keV Gaussian corresponding to the fluorescent Fe K/ $\alpha$  emission with column density  $N_H \sim 5.6 \times 10^{22} \text{ cm}^{-2}$ . The thermal flux of absorption-corrected spectrum integrated over the box shown in Figure 1, between 0.5 and 10 keV give  $2.7 \times 10^{-11}$  and  $1.8 \times 10^{-11}$  ergs  $\text{cm}^{-2} \text{ s}^{-1}$  for the low and high temperature components, respectively. Alternative spectral fitting using weighted response files was done with a combination of a power-law with a photon index  $\alpha = 1.38$ , a single temperature of 0.97 keV and a 6.4 keV Gaussian line with  $N_H \sim 6.8 \times 10^{22} \text{ cm}^{-2}$ . The flux of absorption-corrected spectrum for 0.97 keV component and the power law component give  $2.3 \times 10^{-10}$  and  $1.6 \times 10^{-11}$  ergs  $\text{cm}^{-2} \text{ s}^{-1}$ , respectively. The 6.4 keV line emission in both models give  $1.2 \times 10^{-12}$  ergs  $\text{cm}^{-2} \text{ s}^{-1}$ . The fitted values are shown in Table 1. Both models give equally well-fit spectra with the value of  $\chi^2 \approx 1.2$ . We also note a strong correlation between the amplitude of the power-law

fit and the strength of 6.4 keV line emission which in turn is correlated spatially with the CS line emission. The spectrum of the X-ray filament which is included in the model fits could not easily be isolated from the contribution from the background diffuse gas. Using different areas around the filament as well as including the filament and the surrounding diffuse cloud, the extracted spectra were fit equally well either by a power law or thermal model and showed similar characteristics to that of the surrounding diffuse gas cloud with  $\alpha$  ranging between 1.3 and 1.4. The only difference in the two fitted spectra is the apparent overabundance of Fe with large error. The contribution of 6.4 keV line which is not resolved from 6.7 keV emission may be responsible for the large error.

## Discussion

The spectrum of the diffuse X-ray emission coincident with the G0.13–0.13 molecular cloud can be satisfactorily modeled as emission from a two-component thermal plasma with temperatures of  $\sim 1$  and 10 keV. Although similar two-temperature models have been invoked previously within the Galactic center region (Koyama *et al.* 1996), the production and confinement of the inferred hot component within the Galactic center region is problematic.

This is also true of the Galactic X-ray ridge emission, but recently it has been demonstrated that bremsstrahlung from low-energy cosmic-ray electrons more naturally explains the spectrum below 10 keV and the strength of the Fe 6.4 keV line (Valinia *et al.* 2000). The nonthermal spectrum below 10 keV is consistent with the power law component detected above 10 keV (Yamasaki *et al.* 1997; Valinia & Marshall 1998). Ginga observations show a hard tail in the spectrum of the inner region of the Galactic center with a power law like spectrum. (Yamauchi *et al.* 1990; Yamasaki *et al.* 1996, 1997).

Here we show that this model also applies to G0.13–0.13. First, we note that the absorption-corrected spectrum is well-fit by a soft thermal component plus a power-law. The photon index of  $\approx 1.38$  is consistent with that expected from bremsstrahlung by low energy ( $\lesssim 100$  keV) cosmic-ray electrons,  $-1.3$  to  $-1.4$  over the range 1–10 keV (Valinia et al 2001). The calculations of Valinia et al yield a photon production rate per H nucleus of  $1.4 \times 10^{-20}$  U( eV cm $^{-3}$  ) ph s $^{-1}$  H $^{-1}$  at 1 keV, and a production of 6.4 keV Fe line photons of  $4.8 \times 10^{-22}$  U( eV cm $^{-3}$  ) ph s $^{-1}$  H $^{-1}$ , where U is the energy density of low energy cosmic-ray electron. Adopting a total mass of G0.13–0.13 of  $10^6 M_{\odot}$  and a distance of 8 kpc, our measured fluxes of the power-law component at 1 keV and in the 6.4 keV line correspond to cosmic-ray energy densities of 1.1 and 1.9 eV cm $^{-3}$  respectively. Solar abundances are assumed in Valinia et al’s calculation, so an iron abundance of twice solar would reconcile the continuum and iron-line fluxes. Although our fit to the thermal component (Table 1) gives a somewhat higher iron abundance, it is poorly determined and in any case could differ from the iron abundance in the cold cloud. Within the uncertainties in the shape of the electron spectrum, the model reproduces the observed ratio of 6.4 keV line to continuum, and requires a reasonable energy density in cosmic-ray electrons. In comparison, we note that Valinia et al (2000) estimate that  $U \sim 0.2$  eV cm $^{-3}$  would be sufficient to explain the galactic ridge emission.

The hypothesized low energy electron population would be the dominant source of ionization and heating within the G0.13–0.13 molecular cloud, explaining in particular the high kinetic temperature ( $\sim 70$  K) of G0.13–0.13 (Oka et al 2001) and possibly the high abundance of SiO emission in the vicinity of the Arc correlating with the distribution of the 6.4 keV line emission (Martin-Pintado *et al.* 1997). The ionization cross section for H $_2$  by electrons is  $2 \times 10^{-17}$  cm $^{-2}$ [ $E$ (keV)] $^{-1}$  (e.g. Voit 1991), and for the electron spectrum of Valinia et al (2000), the ionization rate is  $\sim 2 \times 10^{-14}$  s $^{-1}$  H $^{-1}$ , 1000 times the value for molecular clouds in the solar neighborhood. The effect on the cloud can be estimated

using the calculations of Maloney, Hollenbach & Tielens (1996; see their eq [15] and Fig 3a) for ionization and heating by X-rays, as the effects are similar. Their results indicate a fractional ionization of  $\sim 10^{-6}$  and a gas temperature of  $\sim 50\text{--}100\text{ K}$ . The enhanced abundance of SiO gas can be explained perhaps by the impact of low energy cosmic rays with dust grains.

The X-ray filament has a similar spectrum to the diffuse emission associated with G0.13–0.13, and so is likely to be produced by the same mechanism. In this scenario, the emission (both in continuum and the 6.4 keV line), which is enhanced by  $\sim 1.5$  times that from G0.13–0.13, is generated in a volume of the cloud containing one percent of its mass,  $\sim 10^4 M_\odot$  of material. The required energy density is therefore increased to  $\sim 150\text{ eV cm}^{-3}$ , still small compared to the  $\sim 3 \times 10^4\text{ eV cm}^{-3}$  of a 1 mG magnetic field. A plausible source of the enhanced cosmic-ray electrons is acceleration at the interaction site between the G0.13–0.13 cloud and the nonthermal filaments radio filaments of the Arc(TUH; Oka *et al.* 2001). The distribution of diffuse and filamentary X-ray gas lying at the edge of the NTFs imply the presence of nonthermal high energy electrons in the vicinity of the diffuse X-ray source. The X-ray filament being distributed parallel to the NTFs is strongly suggestive of an interaction of X-ray gas with nonthermal filaments. In particular the displacement of the X-ray and radio filaments from each other suggest that the high-energy component of the cosmic ray electrons produce synchrotron radio emission from highly organized magnetic field whereas the low-energy cosmic ray electrons produce bremsstrahlung emission from the edge of the CS G0.13–0.13 cloud. The local cloud material is heated to  $\sim 3000\text{ K}$ , and is predicted to be predominantly atomic with a fractional ionization  $\sim 10^{-2}$  (Maloney et al 1996).

The G0.13–0.13 cloud and the diffuse and filamentary X-ray features lie within the 95% error circle of the unidentified EGRET source 3EGJ1746–2851. This suggests that the

source arises as a result of the interaction of the filament with the cloud. The  $E^{-1.7}$  photon spectrum of 3EGJ1746–2851 matches onto the cloud spectrum at about 10 keV when extended down to X-ray energies. This suggests that the EGRET source is also produced by brehmsstrahlung, and that the electron spectrum extends up to GeV energies (to  $E_{\text{max}}$ , say), with an  $E^{-1.7}$  dependence in this range. The required energy density in high-energy electrons is  $\approx 30E_{\text{max}}/(100 \text{ GeV}) \text{ eV cm}^{-3}$ . This model is supported by the spectral index measurements of the nonthermal filaments between cm and mm wavelengths. The spectral indices ( $p$ , where  $S_\nu \propto \nu^p$ ) are positive along the vertical filaments of the Arc but there is an anomalous filament near G0.16-0.15 with  $p \sim -0.35$  (Anantharamaiah *et al.* 1992), consistent with synchrotron emission from GeV electrons with an  $E^{-1.7}$  spectrum. Close inspection of the spectral index map of Anantharamaiah *et al.* indicates a value similar to that of the anomalous filament near the X-ray filament. Future high resolution spectral index measurements of this region should give a more accurate value of  $p$  in this unusual region.

We have shown that the strong Fe 6.4 keV line emission from the G0.13–0.13 cloud can be explained by impact ionization by low-energy cosmic-ray electrons. A similar interpretation may well be applicable to the diffuse line emission detected from other galactic center molecular clouds, notably Sgr B2 and Sgr C and throughout the inner two degrees of the Galactic center (e.g. Murakami *et al.* 2001a,b; Wang, Gothelf and Lang 2002). This has been interpreted in terms of fluorescent emission resulting from irradiation by an intense source of hard X-rays (Sunyaev, Markovitch and Pavlinsky 1993; Koyama *et al.* 1996). As no such source is apparent, it has been hypothesised that a transient source, perhaps associated with Sgr A\* is responsible. However, a low-energy cosmic-ray electron population permeating the galactic center region would explain this. The geometry of the 6.4 keV emission from the NE edge of the CS cloud is not consistent with a powerful flare from the Galactic center. The excess of supernova remnants detected in the Galactic center



region (Gray 1994) is likely to be responsible for enhancing the flux of high energy cosmic ray particles in the central regions of the Galaxy.

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Fig. 1.— (left panel) Full-resolution image of the filtered x-ray data. The region was chosen to fully include the CS (1–0) emission from G0.13-0.13 (Tsuboi *et al.* 1997). The filament is visible near the northeast border of the region. (right panel) Adaptively-smoothed, exposure-corrected image of the X-ray emission with identical border as in the left panel.

Fig. 2.— Contours of CS (1–0) molecular gas (Tsuboi *et al.* 1997) integrated over the velocity range between 15 and 45  $\text{kms}^{-1}$  superimposed on the smoothed distribution of X-ray gas between 0.5 and 9 keV. The cross coincides with the error bar containing the 95% confidence contour of 3EGJ1746-2851 (Hartman *et al.* 1999).

Fig. 3.— (left panel) The grayscale shows the distribution of the normalization of the 6.4 keV gaussian fit to each of the 81 ( $9 \times 9$ ),  $50''$  spectra. To fit the spectra, a template spectrum was extracted from the rectangular region shown in figure 1. The normalization of the gaussian line and continuum was allowed to vary. The grayscale range is between  $1 \times 10^{-8}$  and  $9.5 \times 10^{-6}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  per  $50^2$  pixel. The fits are restricted to energies from  $\approx 4$ –9 keV in order to avoid the more variable, thermally dominated portions of the spectra from 1–4 keV. (right panel) The grayscale shows an adaptively smoothed image of all X-ray photons with energy from 6.15-6.65 keV, after removing the point sources. The contours show the distribution of the CS(1-0) emission. The grayscale range is between  $4 \times 10^{-11}$  and  $1.3 \times 10^{-9}$  photons  $\text{cm}^{-2} \text{s}^{-1}$  per  $0.5^2$  pixel.

Fig. 4.— Contours of X-ray filament with a spatial resolution of  $2.5'' \times 2.5''$  are superimposed on a  $\lambda 20\text{cm}$  VLA image of the nonthermal filaments of the Arc with a resolution of  $10''$ .

Fig. 5.— Background subtracted, ACIS spectrum of the CS-emitting region as shown in a box in Figure 1. Solid line shows the fit of the absorbed 1-temperature/power-law plus 6.4 keV Gaussian source model. This figure is shown only in electronic version of this paper.